



Enteric methane emissions and their response to agro-ecological and livestock production systems dynamics in Zimbabwe

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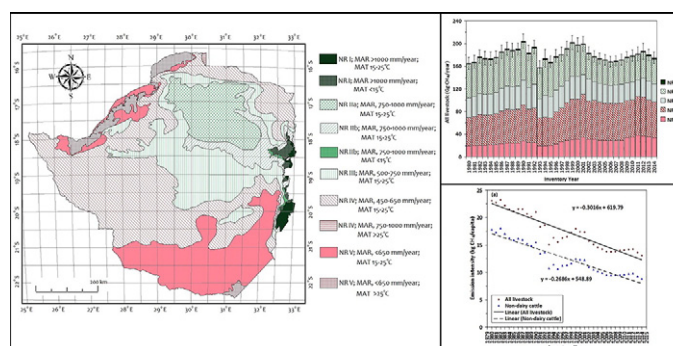
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HIGHLIGHTS

- Per capita emissions are decreasing at -0.3 kg CH_4 per year.
- Domestic meat export was not a significant emissions driver.
- Emissions were responsive to climate variables in drought years.

GRAPHICAL ABSTRACT



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ABSTRACT

Without disregarding its role as one of the key sources of sustainable livelihoods in Zimbabwe and other developing countries, livestock production contributes significantly to greenhouse gas (GHG) emissions through enteric fermentation. For the livestock sector to complement global efforts to mitigate climate change, accurate estimations of GHG emissions are required. Methane emissions from enteric fermentation in Zimbabwe were quantified over 35 years under four production systems and five agro-ecological regions. The Intergovernmental Panel on Climate Change emission factor methodology was used to derive CH_4 emissions from seven livestock categories at national level. Emission intensities based on human population, domestic export of livestock meat and climate variables were used to assess emission drivers and predict future emission trends. Over the past 35 years, enteric fermentation CH_4 emissions from all livestock categories ranged between 158.3 and 204.3 Gg year^{-1} . Communal lands, typified by indigenous livestock breeds, had the highest contribution of between 58% and 75% of the total annual emissions followed by livestock from large scale commercial (LSC) farms. The decreasing livestock population on LSC farms and consequent decline in production could explain the lack of a positive response of CH_4 emissions to human population growth, and decreasing emissions per capita over time at $-0.3 \text{ kg CH}_4 \text{ capita}^{-1} \text{ year}^{-1}$. The emissions trend showed that even if Zimbabwe's national livestock population doubles in 2030 relative to the 2014 estimates, the country would still remain with similar magnitude of CH_4 emission intensity as that of 1980. No significant correlations ($P > 0.05$) were found between emissions and domestic export of beef and pork. Further research on enhanced characterisation of livestock

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species, population and production systems, as well as direct measurements and modelling of emissions from indigenous and exotic livestock breeds were recommended.

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1. Introduction

Feed production and processing and enteric fermentation from domesticated ruminants constitute 45 and 39% of total global agriculture greenhouse gas (GHG) emissions, respectively (Gerber et al., 2013). In Zimbabwe, the livestock sector is a notable primary industry responsible for emitting over 60% of agricultural GHG emissions (4000 Gg of carbon dioxide (CO₂) equivalents) annually in the past two decades through enteric fermentation (MMET, 1998; MENRM, 2012; MEWC, 2016). In this period, the contribution of livestock enteric fermentation to national GHG emissions increased from about 12% to 19%. However, in view of the livestock sector's high vulnerability to climate change, particularly in southern Africa (Jury, 2013), the livestock industry stands to benefit considerably from climate change mitigation. The sector must therefore complement global efforts to reduce methane (CH₄) emissions in the long-term. Some researchers have argued that livestock hold as much as 50% of the technical mitigation potential of the combined forestry, land-use and agricultural sectors, through dietary changes and other interventions (Hristov et al., 2013; Herrero et al., 2016). In order to evaluate this mitigation potential at national level, a better understanding of the GHG emission dynamics and their drivers in the livestock sector is required.

Under the provisions of the Paris Agreement (UNFCCC, 2015), Zimbabwe has set a 33% GHG emission intensity reduction target in its Nationally Determined Contributions (MEWC, 2015). This target was specifically intended for the energy sector that contributes the highest GHG emissions. Emissions from energy uses in the manufacturing and construction category contributed 36% of the national emissions in 2000 (MENRM, 2012), but this contribution dropped to about 7% in 2006 (MEWC, 2016). This reduction in GHG emissions from the manufacturing and construction category was due to the closing of some industries due to economic challenges, and may explain why the enteric fermentation category was ranked the second highest emitter of GHGs in Zimbabwe, after the energy industries category. However, before setting up any mitigation targets for the livestock sector, the country requires more location-specific GHG inventories for its livestock systems. This would allow for the targeting of livestock systems and regions with relatively high mitigation potentials.

Zimbabwe has reported its national GHG emissions from the livestock sector using a 'Tier 1' approach based on livestock populations, emission factors and other relevant parameters using the Revised 1996 Intergovernmental Panel on Climate Change (IPCC) Guidelines (IPCC, 1997). However, the reported emissions do not adequately incorporate the dynamics in livestock production systems and the geographical distribution of livestock population (MMET, 1998; MENRM, 2012; MEWC, 2016). Livestock systems and their specific agro-ecological regions are critical factors in predicting the biochemical processes leading to CH₄ emissions from livestock. Incorporation of these factors in GHG inventories permits the use of updated and more region-specific emission factors. It is also a starting point in establishing country-specific emission factors and related parameters.

The objective of this study was to quantify CH₄ emissions from livestock enteric fermentation at national level under different livestock production systems and agro-ecological regions. The annual dynamics in CH₄ emissions were hypothesized to be a reflection of human population growth, climate variability, changes in livestock ownership, livestock geographical re-distribution and domestic export trends of livestock products in the past three-and-half decades. This study was intended to complement global efforts towards GHG

mitigation through identification of possible drivers of CH₄ emissions in the livestock sector.

2. Materials and methods

2.1. Agro-ecological regions and livestock production systems in Zimbabwe

Zimbabwe's land area was subdivided into five Natural Regions (NRs) on the basis of mean annual rainfall, temperature and other agro-ecological factors (Vincent and Thomas, 1961) (Fig. 1). Up to 65% of the country's total land area is covered by NRs IV and V that are suitable for semi-extensive and extensive livestock production due to palatable, sweet grass, while about 17% forms the high grain-producing NRs I and II that are suitable for intensive livestock production (ZIMSTAT, 2015). The remaining area falls under NR III that is suitable for semi-intensive livestock production. Beef cattle (hereinafter referred to as non-dairy cattle) and indigenous pigs and chicken are raised on natural pastures across all NRs, but predominantly in NRs III, IV and V. Dairy cattle and exotic pigs and chicken are produced from grain- and cereal-based feedstuffs. Natural rangeland (veld) do not only cover more than two-thirds of total land area, but also provide the relatively high-quality sweet-veld that promote higher live weight gains than the sour-veld in the high rainfall regions (Gambiza and Nyama, 2006). While a decline in land areas under NR II and III in favour of the relatively dry NRs IV and V has been reported (Mugandani et al., 2012), evidence to support these changes is still limited. As a result, the current study was based on the five NRs classified by Vincent and Thomas (1961).

Livestock production in Zimbabwe is classified into four major production systems (Table 1) and all production systems were considered in this study. The Communal Lands consist of farmers in a village setting with individual cropping areas, but common grazing areas. About 74% of Communal Lands are in the semi-arid NRs IV and V (ZIMSTAT, 2015). The majority of farmers in this category are considered to be smallholder farmers. FAO (2004) defined smallholder farmers as those farmers with relatively limited resources, cultivating from <1 up to 10 ha, and managing up to 10 head of livestock. Included in this definition are farms under the 'A1' communal resettlement model. The 'A2' resettlement model, with crop and livestock production on the same farm, has relatively large farm sizes of above 100 ha on average. The 'A1' and 'A2' Farms started in 2000 and were considered separately from the Old Resettlement Schemes that were established between 1982 and 1998, except for the period 2000 to 2008. For this period the 'A1' and 'A2' Farms were combined under 'Resettlement Schemes' (RS) due to lack of disaggregated data.

2.2. Data gathering and management

The key data for computation of CH₄ emissions from enteric fermentation was livestock population from four major data sources and covering dairy cattle, non-dairy cattle, goats, sheep, pigs, donkeys and horses. The first data source was the Zimbabwe National Statistics Agency (ZIMSTAT), a semi-autonomous agency of the Government of Zimbabwe, formally called the Central Statistics Office (from 1948 to 2007). The livestock surveys data collected at national level and published at each year ending 31 March by ZIMSTAT was obtained for the period 1980 to 2014. The data was disaggregated according to the identified livestock production systems (Table 1) and according to NRs. In the cases where there was missing data or aggregated data, interpolation

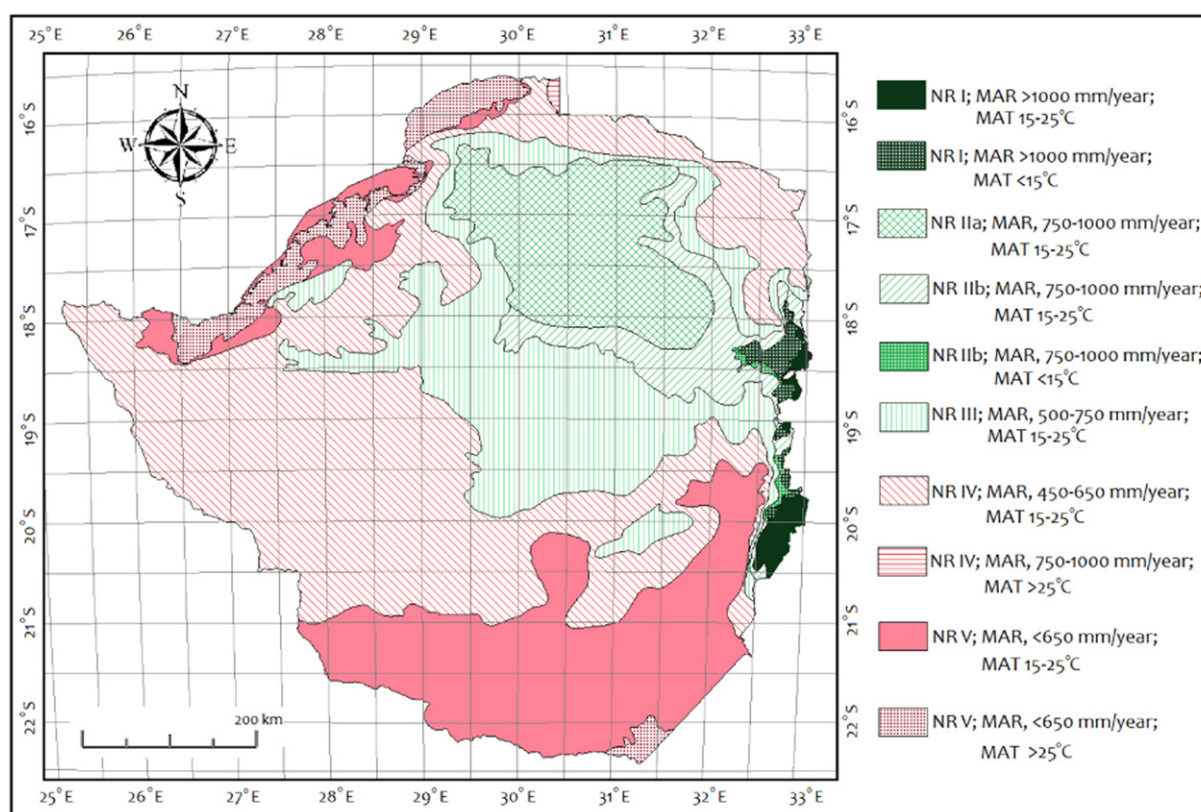


Fig. 1. Mean annual rainfall (MAR) and mean annual temperatures (MAT) of Zimbabwe's five Natural Regions (NRs I–V) for the period 1961–1990. (Modified after Vincent and Thomas, 1961; IPCC, 2006b; WTP (2007)).

methods and the mean livestock population ratios in different NRs and production systems were used to fill-in the data gaps.

The second and third data sources were the Division of Veterinary Services and Livestock Production and Development (DVS-LPD) and the Department of Agricultural Technical and Extension Services

(AGRITEX), both under the Ministry of Agriculture, Mechanisation and Irrigation Development. The DVS-LPD in general use dip-tanks as census points for cattle, and also conduct national livestock surveys at regular intervals. The data was provided as electronic spread-sheets and it was largely aggregated. In some years, data disaggregated into district

Table 1
Selected characteristics of the four main livestock production systems in Zimbabwe.

Livestock farming system	Year	Total area (km ²)	Number of farms	Mean farm size (Ha)	Cattle statistics from surveys		References
					Farm count	Cattle number	
Large Scale Commercial Farms (LSCF)	1984	157,000	6000	2200	4334	2,033,455	CSO (1984a, 1985)
	1997	123,400	5146	2296	3933	1,409,288	CSO (1998, 2000a)
	2000	112,900	4649	2249	3481	1,243,795	CSO (2000a, 2001)
	2012	88,600	3994	2219	973	156,335	ZIMSTAT (2013a, 2016a)
Small Scale Commercial Farms (SSCF)	1984	14,200	8500	125	7145	35,309	CSO (1984a, 1985)
	1997	14,200	9650	148	7821	185,013	CSO (1998, 1999a)
	2000	14,200	9655	148	7222	171,678	CSO (2001, 2005)
	2012	14,200	9655	148	8712	133,046	ZIMSTAT (2013a, 2016b)
Communal Lands (CL)	1984	163,500	N/D	23	N/D	3,231,000	CSO (1985)
	1997	163,500	N/D	23	532,553	3,427,447	CSO (1998, 1999b)
	2000	163,500	N/D	23	601,813	3,971,719	CSO (2001, 2000b)
	2012	163,500	N/D	23	688,464	4,223,309	ZIMSTAT (2013a, 2016c)
^a Resettlement Schemes (RS)	1984	N/D	N/D	N/D	N/D	178,000	CSO (1985)
	1997	33,600	247	N/D	N/D	323,607	CSO (1998, 1999c)
	2000	44,100	N/D	N/D	N/D	486,500	CSO (2001)
	2012	68,400	N/D	N/D	160,405 ^b	1,690,812 ^c	ZIMSTAT (2013a, 2016d, 2016e, 2016f)

N/D = No data found.

^a The Resettlement Schemes include the: (1) Old Resettlement Schemes under model A (5 ha arable plus common grazing), models B and C (farming co-operatives), model D (cattle ranching area) and model E (individual farmer with crop and livestock production on the same farm, similar to large-scale and small-scale farms); (2) A1 farms (6 ha arable plus common grazing); and (3) A2 farms (similar to small-scale and large scale farms).

^b This value is the sum of 56,963 farms from Old Resettlement Schemes, 88,082 farms from A1 resettlement model and 15,360 farms from A2 resettlement model.

^c This value is the sum of 42,9007 cattle from Old Resettlement Schemes, 903,984 cattle from A1 farms and 357,821 cattle from A2 farms.

and province boundaries (political administration boundaries) was also available. Data from the DVS-LPD was disaggregated into NRs and production systems using the population ratios obtained from the ZIMSTAT data while interpolation was also used in data gap filling. Livestock population data obtained from AGRITEX was collected jointly with the Food and Agriculture Organisation of the United Nations (FAO) and other relevant government departments and development agencies through the Crop and Livestock Assessments (CLAs). The CLAs are conducted during the first week of February (First Round Assessment) and during the second week of April (Second Round Assessment) annually. Data files from AGRITEX were provided by the department and were also available from online reports. The last data source was the FAO's online database (FAOSTAT, 2017a). Livestock data from FAO was aggregated for each reporting year ending 30 September. Disaggregation of the data from these sources, into NRs and production systems, was done using population ratios from ZIMSTAT data.

2.3. Emission factors and computation of GHG emission estimates

The emission factors used in the computation of CH₄ emissions from enteric fermentation are given in Table 2. Emissions were calculated separately for each data source using the 2006 IPCC Guidelines (IPCC, 2006a). The general methodology disaggregated emissions from each livestock category according to NRs and production systems using population ratios from ZIMSTAT data. The disaggregation of livestock data allowed for the use of more region-specific emission factors for non-dairy cattle. The emission factor for dairy cattle was selected based on literature data and taking into consideration the circumstances of smallholder farmers who have greatest proportion of lactating cows according to ZIMSTAT livestock population inventories. Typical milk yield of indigenous cows was reported to be 3–4 kg day⁻¹ over a lactation period of 150 days (Mutukumira et al., 1996). Average milk production in Communal Lands was taken to be 2.61–2.67 L day⁻¹ over 161–182 days of lactation in NR IV and 1.5 L day⁻¹ over 180 days in NR II (Barrett, 1992).

2.4. Emission intensities

Annual CH₄ emissions from livestock enteric fermentation were rated against the national human population to derive emissions *per capita* between 1980 and 2014. National human census data was obtained for 1982 (CSO, 1984b), 1992 (CSO, 1994), 2002 (CSO, 2004) and 2012 (ZIMSTAT, 2013b). The data was gap-filled using population growth rates from the same reports and other inter-censal demographic survey reports from ZIMSTAT. Methane emissions were also rated against the annual quantities of domestic export of meat to establish if the export market has been a significant driver of livestock production, hence enteric fermentation, at national level. Specific meat export data

was available for only beef and pork from the FAO online database (FAOSTAT, 2017b). The national average annual rainfall and temperature data for the period 1980 to 2014 was downloaded from the World Bank's Climate Change Knowledge Portal (World Bank, 2017). The data was used to assess the response of livestock population, and their subsequent CH₄ emissions, to climate variables at national level.

2.5. Data analyses

Annual population data from different livestock categories was tested for normality using the Shapiro-Wilk's test at 5% significance level. The probability density function of emission factors was assumed to follow a normal distribution. Uncertainties of activity data were calculated as the standard deviation of the mean of activity data from three sources. The Monte Carlo analysis (IPCC, 2000) was used to combine uncertainties from the activity data and emission factors because the activity data did not follow a normal distribution. Bivariate correlation analysis (two-tailed) was performed using the nonparametric Spearman's Rank Correlation analysis to establish the correlation between the emissions and population, mean annual rainfall, mean annual temperature and domestic export of beef and pork at 5% significance level. Regression analysis was performed to establish the strength of linear relationships between variables. The SPSS software (version 16.0.0; SPSS Inc., USA) was used in the statistical analyses of data.

3. Results

3.1. Zimbabwe's livestock population dynamics

Smallholder farmers, primarily on Communal Lands, dominated livestock ownership over the past 35 years (Fig. 2). These farmers had relatively few livestock heads per farmer, but >100-fold the farmer-counts per livestock category of other farmers. The livestock inventory data from ZIMSTAT showed that up to 688,464 and 693,265 households from Communal Lands owned non-dairy cattle and goats, respectively, compared with 1218 and 603 farms with non-dairy cattle and goats, respectively, under the Large Scale Commercial sector. The proportions of cattle, pigs and sheep owned on Large Scale Commercial farms decreased with time, and decreased abruptly after the onset of the 2000 Land Reform Programme. The rate of decline in the number of livestock owned on Large Scale Commercial farms was considerably higher than the rate of livestock population growth under the 'A1' and 'A2' resettlement schemes (A1F and A2F).

Over 80% of the goats, sheep and donkeys population were in the relatively dry NRs III, IV and V, while on average about 50% of the pigs population were in the same NRs. The proportions of cattle population in NRs III, IV and V were 70–80% for dairy cattle and 60–70% for non-dairy cattle. Changes in the distribution of cattle, pigs and sheep

Table 2

Emission factors (and their uncertainty levels) used to compute CH₄ emissions from enteric fermentation in different Natural Regions (NRs).

Livestock category	Emission factor (kg CH ₄ /head/yr)	^a EF IPCC No.	NR	Conditions and regions
Dairy cattle	36.0 ± 7.2	43,116	All	Grazing with low production per cow; commercialised dairy sector; milk = 475 kg/head/yr; Africa and Middle East
Non-dairy cattle_1	26.0 ± 3.9	421,099	III, IV, V	Semi-arid rangeland; no supplementary feed; live weight = 250 kg; milk <2 kg/day; southern Africa, including Zimbabwe
Non-dairy cattle_2	33.00 ± 4.95	421,104	I, II	Humid rangeland; no supplementary feed; live weight = 250 kg; milk <2 kg/day; southern Africa, including Zimbabwe
Goats	5.0 ± 1.0	43,093	All	Developing countries
Sheep	5.0 ± 1.0	43,091	All	Developing countries
Mules and donkeys	10.0 ± 2.0	43,099	All	Developing countries
Pigs	1.0 ± 0.2	43,101	All	Developing countries
Horses	18.0 ± 3.6	43,097	All	Developing countries

^a EF IPCC No. = Emission factor identity number from the emission factor database (IPCC, 2017). No country-specific emission factor was available for all livestock categories.

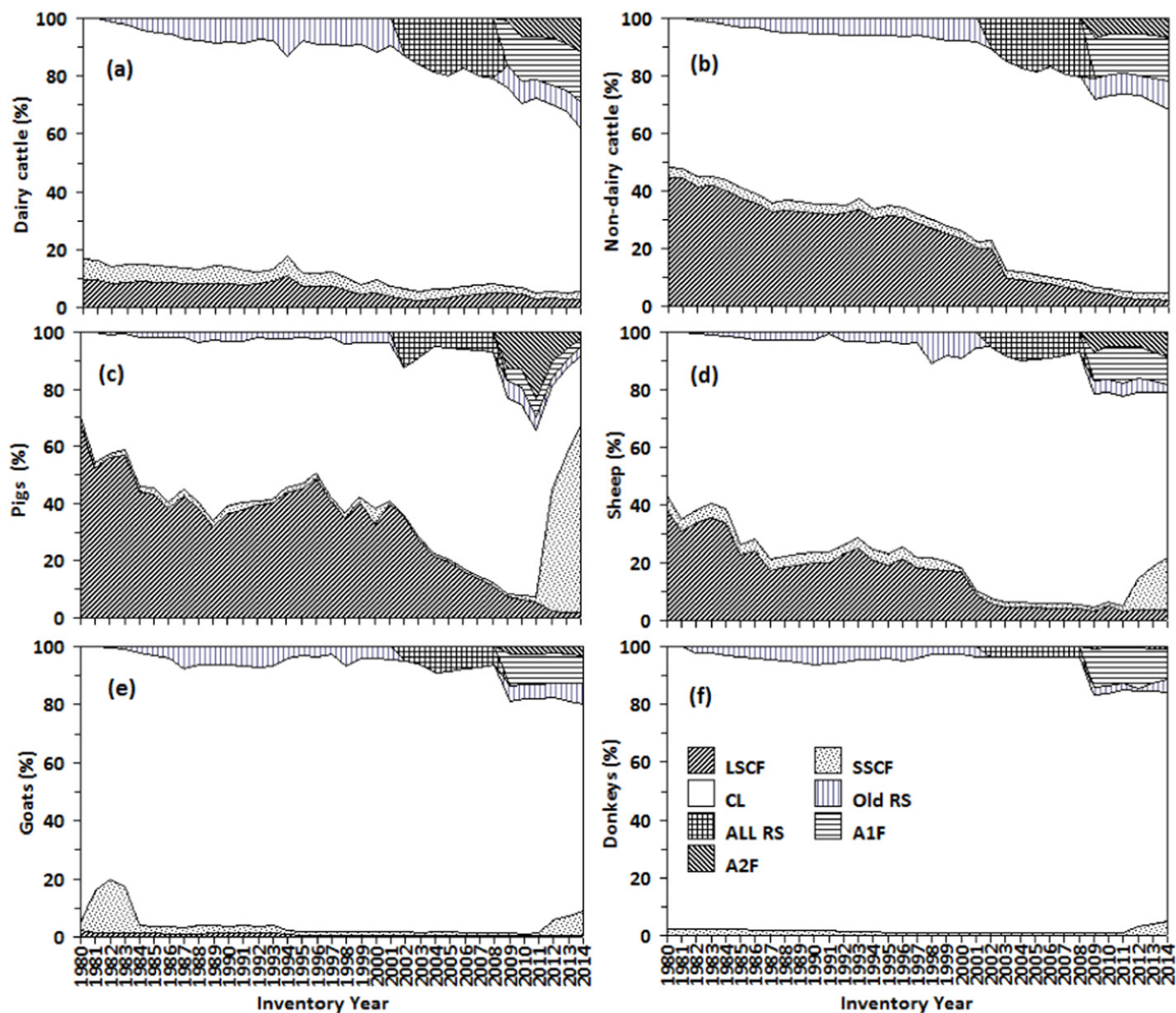


Fig. 2. Zimbabwe's livestock population distribution according to farming systems over 35 years (LSCF = Large scale commercial; SSCF = Small scale commercial; CL = Communal lands; RS = Resettlement schemes; A1F = A1 farm; A2F = A2 farms).

among the NRs were noted, particularly during the periods 1993–1995 and 2000–2012, while the distribution of donkeys and goats remained relatively constant over the years. During the period 1993–1995, some proportion of dairy cattle, non-dairy cattle and pig population were lost from NRs IV and V to NR II. Gradual gains in non-dairy cattle, pigs and sheep were noted in NRs IV and V during the period 2000–2012, and these gains corresponded to declining proportion of these livestock categories in NR II.

3.2. Total CH_4 emissions from enteric fermentation

Over the past 35 years, enteric fermentation from all livestock categories emitted ranged from $158.3 \text{ Gg CH}_4 \text{ year}^{-1}$ in 1993 to $204.3 \text{ Gg CH}_4 \text{ year}^{-1}$ in 1990 (Fig. 3). The contribution of each livestock category to total annual emissions decreased in the order: non-dairy cattle (67–78%) > dairy cattle (16–19%) > goats (3–13%) > donkeys = sheep (1–2%) > horses = pigs (<1%). The emissions were below the first-quartile ($173.9 \text{ Gg year}^{-1}$) during the periods: 1980–1981, 1984, 1993, 1995 and 2005–2007. A gradual increase in CH_4 emissions at a rate of

4.0 Gg year^{-1} was noted from 1983 to 1990 (linear regression $R^2 = 0.88$), before the fall in 1993 after the country experienced a drought year. A similar increase in CH_4 emissions was noted from 1994 to 1999 at 6.5 Gg year^{-1} ($R^2 = 0.91$) before falling in 2000 when the 'Fast Track' Land Reform Programme started. From 2000 the emissions decreased at a linear rate of $-5.5 \text{ Gg year}^{-1}$ ($R^2 = 0.90$) up to 2007. Between 2007 and 2012 emissions increased slowly at 3.4 Gg year^{-1} ($R^2 = 0.99$), before another downward emissions trend from 2012 to 2014.

3.3. Livestock production systems emissions

Livestock from Communal Lands had the highest contribution of between 58% and 75% of the total annual emissions between 1980 and 2014, followed by livestock from Large Scale Commercial farms (Fig. 3a). The Large Scale Commercial farms livestock contributed up to 38% of the emissions in 1980, but the contribution decreased to 2% in 2014. There was a notable fall-down in livestock production on Large Scale Commercial farms that emitted $62.8 \text{ Gg CH}_4 \text{ year}^{-1}$ in

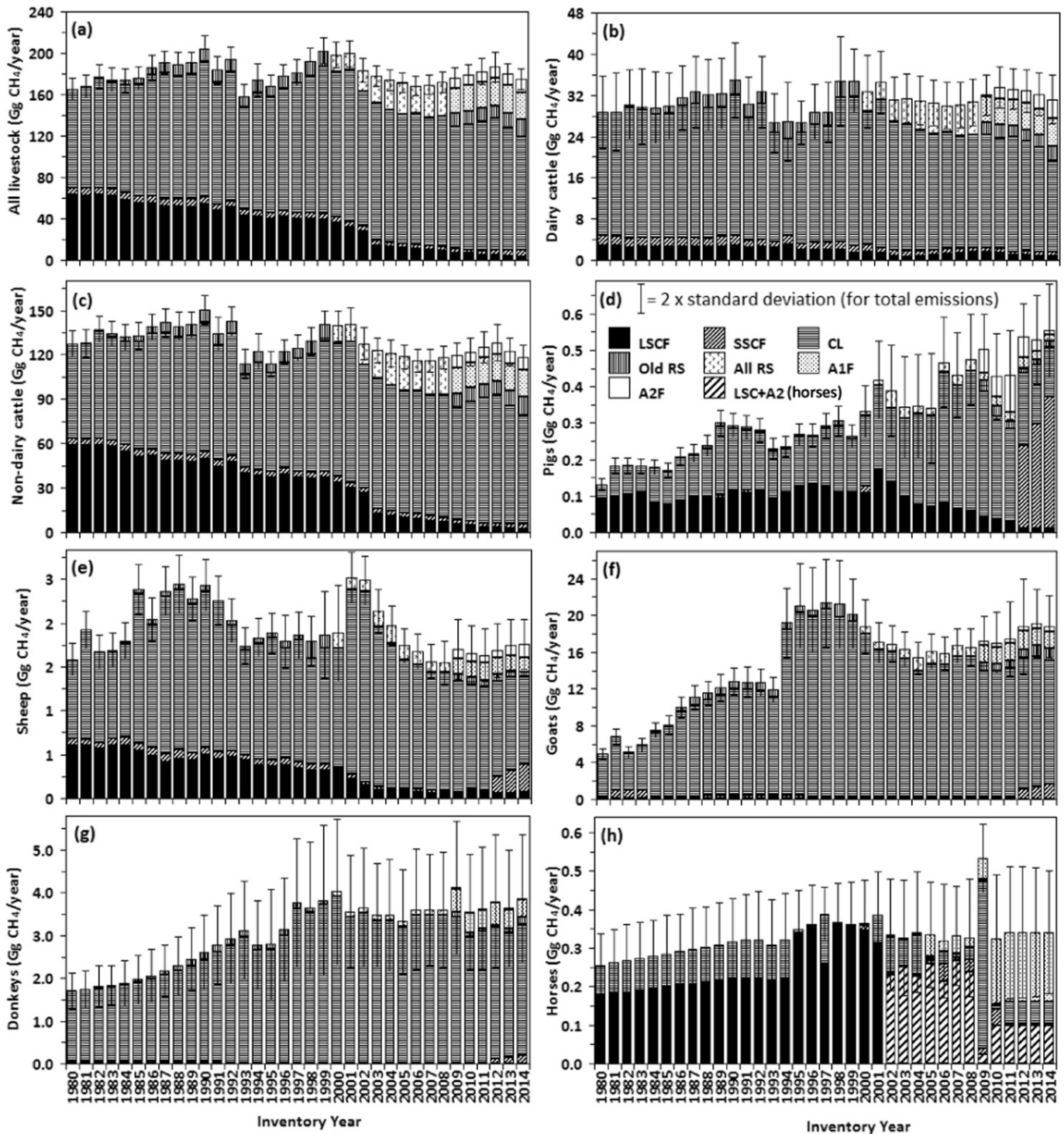


Fig. 3. Emissions of CH_4 from enteric fermentation according to livestock and production system over 35 years (LSCF = Large scale commercial; SSCF = Small scale commercial; CL = Communal lands; RS = Resettlement schemes; A1F = A1 farm; A2F = A2 farms).

1980, to make provisions for the 'A1' and 'A2' farms that emitted 26.1 and 12.7 $\text{Gg CH}_4 \text{ year}^{-1}$ in 2014, respectively. Contribution of livestock from other production systems followed the order: all Resettlement Schemes from 2001 to 2009 (8–19%) > 'A1' farms from 2010 to 2014 (14–15%) > old Resettlement Schemes from 1983 to 2000 and from 2010 to 2014 (1–10%) > 'A2' farms from 2010 to 2014 (5–7%) > Small Scale Commercial farms from 1980 to 2014 (2–5%). Among the small ruminants, the steepest increase in emissions ($0.92 \text{ Gg year}^{-1}$) was noted for goats between 1983 and 1991

($R^2 = 0.95$) (Fig. 3f), and this was largely the contribution from Communal Lands.

3.4. GHG emissions from livestock disaggregated by agro-ecological regions

The contribution of all livestock to CH_4 emissions by enteric fermentation under different NRs between 1980 and 2014 decreased in the order: NR IV (24–36%), NR II (24–36%), NR III (16–22%), NR V (11–21%) and NR I (<2%) as shown in Fig. 4a. However, under the non-

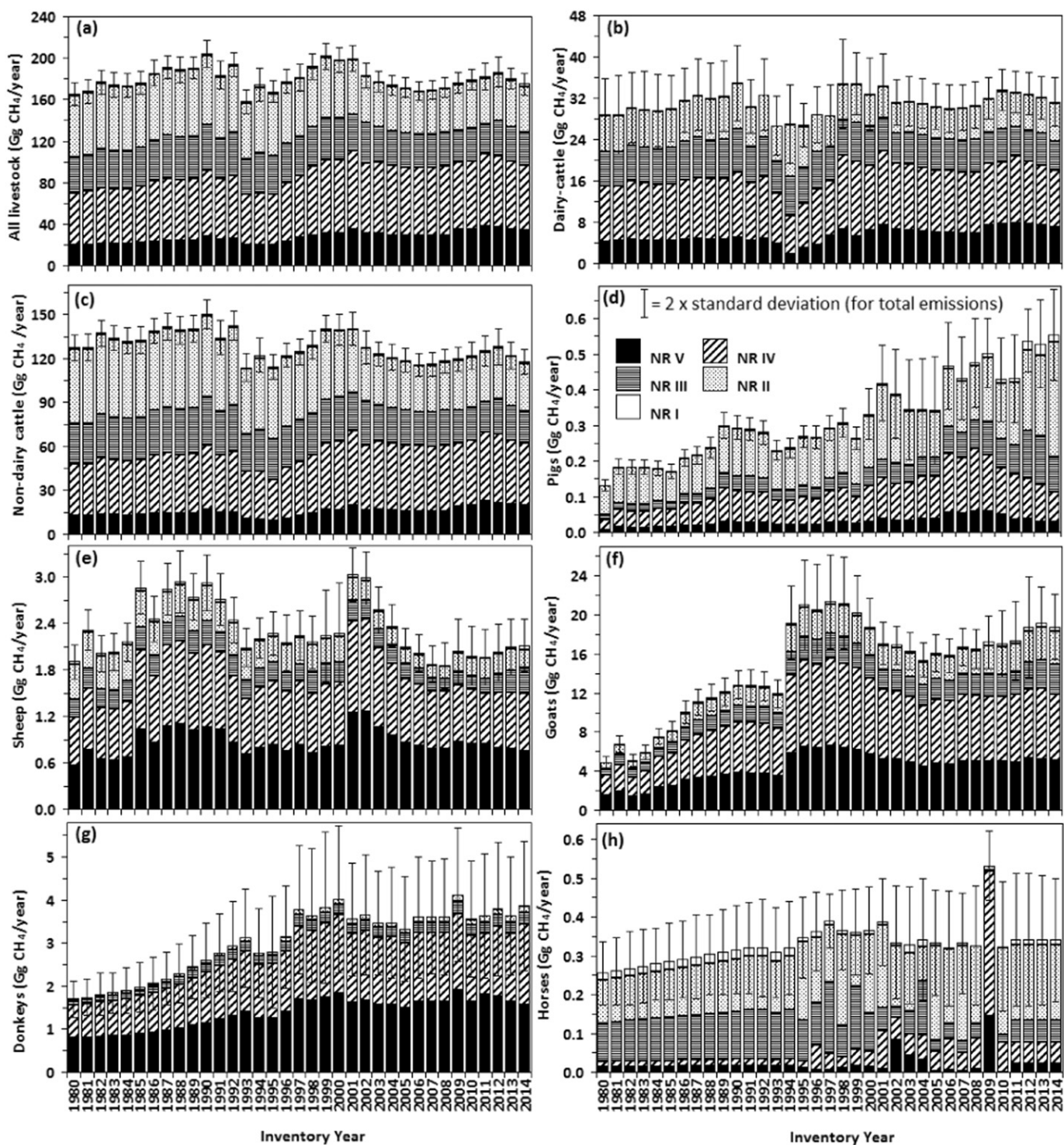


Fig. 4. Methane emissions from livestock enteric fermentation according to Natural Region (NR) and livestock category over 35 years.

dairy cattle category that emitted the highest CH₄ emissions of 113.8–150 Gg year⁻¹ (Fig. 4c), NR II had the highest contribution of 27–42% of emissions. This was followed by non-dairy cattle from NR IV (25–39%). The highest emissions from pigs and horses enteric fermentation also came from NR II over the past 35 years (Fig. 4d and h).

3.5. GHG emission intensities

There were no significant correlations ($P > 0.05$) between the emissions from cattle and pigs, and amount of domestic export of beef (0–

12.1 Tg year⁻¹) and pork (0–2.3 Tg year⁻¹), respectively. The domestic export of beef was relatively high between 1980 and 1985 (1.0–12.1 Tg year⁻¹), but thereafter did not exceed 0.1 Tg year⁻¹ with the exception of year 2000 (0.7 Tg) and year 2002 (also 0.7 Tg). The increased beef export during the years 2000 to 2002 coincided with the changes in the Large Scale Commercial farms following the 'Fast Track' Land Reform Programme. The domestic export of pork was relatively high between 1995 and 2003, with the highest amounts exported in 1996. However, there was also no evidence that CH₄ emissions from enteric fermentation were driven by the domestic export market for pork.

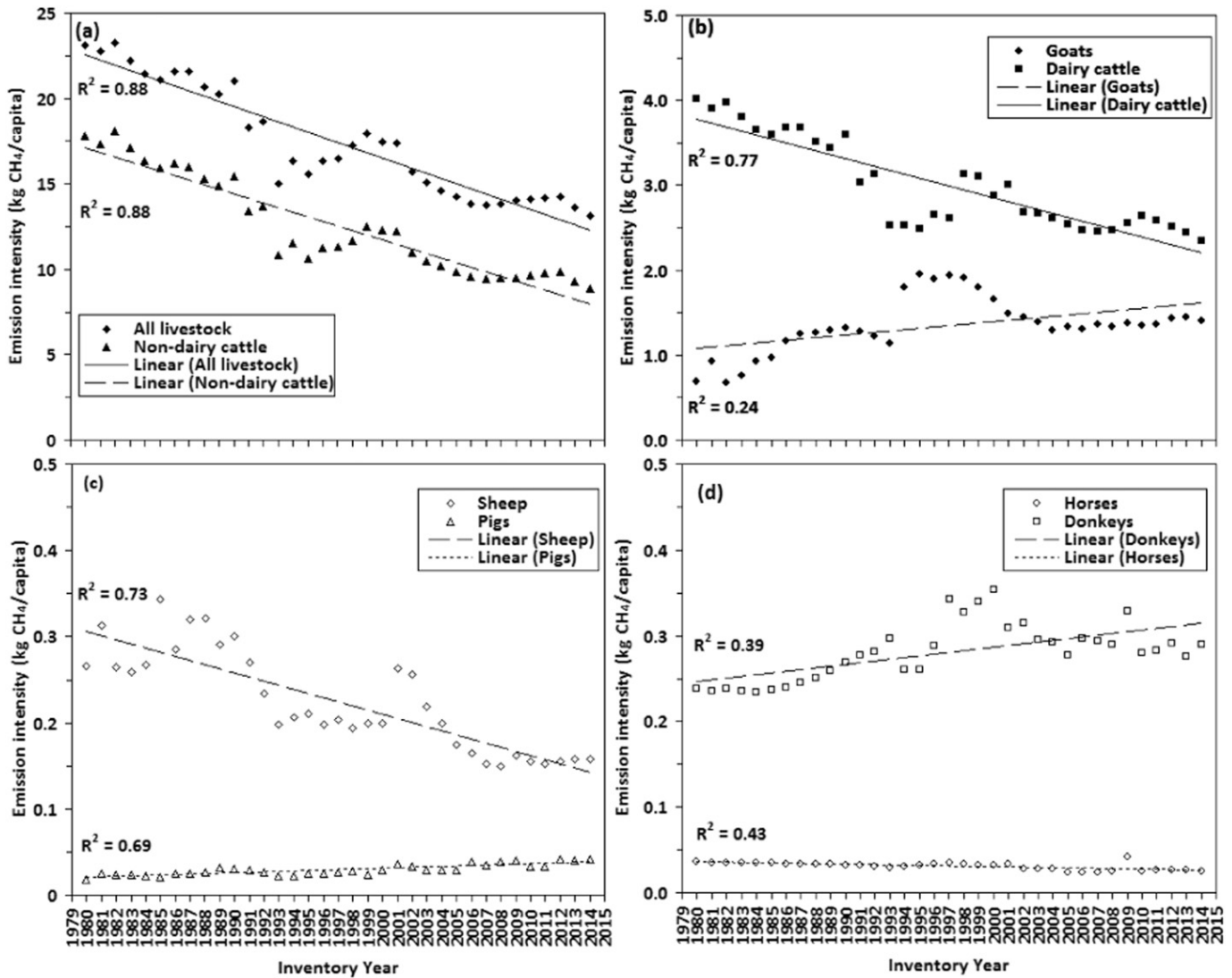


Fig. 5. Changes in CH₄ emission intensities per livestock category and their linear regression trends between 1980 and 2014.

The relationship between human population and CH₄ emissions from livestock enteric fermentation indicated that population growth, from about 7.2 million people in 1980 to about 13.4 million in 2014, was not a significant driver of emissions from dairy cattle, non-dairy cattle, sheep and horses. The *per capita* emissions from livestock enteric fermentation decreased with time for these four livestock categories, but the reverse was noted for goats, pigs and donkeys (Fig. 5). Overall the linear regression analysis showed that CH₄ emissions decreased at a rate of $-0.30 \text{ kg capita}^{-1}$ each year during the period 1980 to 2014 (Fig. 5a).

There were no significant correlations ($P > 0.05$) between CH₄ emissions from all livestock categories and the mean annual rainfall that ranged from 418 to 923 mm year⁻¹. The national mean annual rainfall was below 500 mm year⁻¹ during the periods: 1982–1983, 1987, 1992, 1994–1995 and 2002, but only the 1994–1995 and the 2002 periods had a marked fall in CH₄ emissions (Fig. 3a). The emissions and the mean annual temperatures (range: 20.7 °C in 1981 to 23.2 °C in 2005) showed significant correlations only for non-dairy cattle in NRs I and II ($P = 0.018$; $r_s = -0.40$), goats ($P = 0.032$; $r_s = 0.36$), pigs ($P = 0.004$; $r_s = 0.47$) and donkeys ($P = 0.020$; $r_s = 0.39$). The linear relationships between these variables were however, relatively weak.

4. Discussion

This study explored the dynamics of livestock population over the past 35 years, and their impact on enteric CH₄ emissions and emission intensities at national level. The results showed that the magnitude of CH₄ emissions from livestock enteric fermentation was more significantly dependent on the Communal Lands production system than on any other livestock system in Zimbabwe.

Communal Lands are typified by indigenous livestock breeds. Researchers have noted that Zimbabwe's indigenous livestock breeds have low feed requirements (e.g. Assan, 2012; Tavirimirwa et al., 2013). These breeds would therefore emit less CH₄ than the “high-yielding breeds” since the amount of feed taken up is proportional to the amount of CH₄ emitted (MacDonald, 2012). However, the findings by Herrero et al. (2016) have shown that in terms of CH₄ emitted per unit mass of edible animal protein, the sub-Saharan Africa region is the global hot-spot for high emission intensities due to low animal productivity. With the declining livestock populations on Large Scale Commercial farms, the future livestock population is likely to remain predominantly that of indigenous breeds. Thus, local research on enteric fermentation using both indigenous and exotic breeds is urgently

required to guide the country's National Inventory Report of GHGs and mitigation programmes for the livestock sector.

Many of the indigenous breeds of livestock such as cattle and donkeys are kept by smallholder farmers for dual purposes, which include provision of draught power and household income. As an alternative to field operations powered by fossil fuels, operations that use draught animals would emit less GHGs. From the mitigation point of view, the GHG emissions foregone using draught animal power can be subtracted from the overall emissions from livestock (Gerber et al., 2013). According to FAO (2000) GHG emission intensities based on CH₄ produced per unit of draught animal power would be more precise than CH₄ produced per unit of meat production due to the diversity of meat sources. More detailed livestock and production system characterisation is required to determine the mitigation potential of draught animal power in Zimbabwe. Nevertheless, the benefits of both the multipurpose nature of indigenous breeds and their relatively low CH₄ emission potential are likely to be upheld in future.

The study found no evidence that CH₄ emissions from enteric fermentation were driven by the domestic export market for beef and pork. However, the Land Reform Programme contributed to the decrease in CH₄ emissions from enteric fermentation between 2001 and 2003. The commercial beef herd on Large Scale Commercial farms numbered 1.66 million in 2000, but was reported at 0.51 million in 2002 as farmers slaughtered their cattle when their farms were allocated for resettlement (Gunjal et al., 2008). The results showed that an increase in beef export does not necessarily translate to an increase in emissions, particularly when domestic export markets are supported by restocking programmes to sustain future beef exporting.

The decreasing CH₄ emission intensities under dairy cattle, non-dairy cattle, sheep and horses implied that livestock population in these categories did not change significantly from their national 35-year averages, despite the increasing human population. Predicting from annual change in emission intensity ($-0.3 \text{ kg CH}_4 \text{ capita}^{-1}$, Fig. 5a), livestock enteric fermentation may contribute about $11.3 \text{ kg CH}_4 \text{ capita}^{-1}$ in 2030, which is about half the contribution in 1980. This is based on the assumption that the livestock populations remain within the 5-year (2010–2014) average that contributes about $180.5 \text{ Gg CH}_4 \text{ year}^{-1}$ via enteric fermentation. It is also assumed that national population will be growing at the rate of $1.1\% \text{ per annum}$, thus 15.9 million people in 2030 (ZIMSTAT, 2013b). This analysis implies that should Zimbabwe's national livestock population double in 2030 relative to the 2014 estimates, the country would still remain with the similar magnitude of CH₄ emission intensity as that of 1980.

5. Conclusion

This study has confirmed that the dynamics of CH₄ emission from livestock enteric fermentation over the past 35-years has been predominantly a reflection of the changes livestock ownership in four production systems. Communal Lands contributed the highest emissions due to the relatively high owner-counts per livestock category. Population growth and domestic export of beef and pork have not been significant drivers of CH₄ emissions from livestock enteric fermentation at national level. The fall-down of livestock production on Large Scale Commercial farms could explain the lack of a positive response of CH₄ emissions to human population growth as well as decreasing emission *per capita*. During the drought years, when annual rainfall dropped below 500 mm, livestock losses from NRs IV and V were more considerable than losses from NR II suggesting high livestock vulnerability in drier agro-ecological regions. Future research efforts need to be directed towards enhanced characterisation of livestock class and production systems and direct measurements and modelling of emissions from enteric fermentation and emission factors in indigenous and exotic livestock breeds.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2017.10.257>.

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